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Influence of the energy management on the sizing of Electrical Energy Storage Systems in an aircraft

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HIGHLIGHTS

- Association of battery and supercapacitor system as energy and power sources in an aircraft.
- Sizing method for Electrical Energy Storage Systems (battery and supercapacitor) to minimize the global weight.
- Influence of an energy management based on a frequency approach on the storage system sizing.
- Assessment of the sizing by simulation at a critical temperature and adaptation of the energy management.

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ABSTRACT

In an aircraft, Electrical Energy Storage Systems (EESS) are used as support to other sources in few mission phases in order to ensure the energy availability. They are also used as electrical smoothing devices in order to guarantee the required levels of reliability, stability and quality for an embedded electrical network. This paper deals with the association of two EESS: supercapacitors and secondary battery, which exhibit complementary properties. In this paper, a sizing method for both EESS is developed by taking into account their hybridization and their characteristics (such as capacity or depth-of-discharge) so as to minimize the global storage system weight. Moreover, an energy management based on a frequency approach is implemented to dispatch the power between all the sources. The influence of this management on the sizing is studied. Indeed the cut-off frequency of the low-pass filter is used as a setting parameter of the sizing algorithm. Finally, the sizing validity is assessed and discussed according to temperature constraints. Although battery performances are reduced at low temperature, the sizing determined with the algorithm at 20 °C is still valid on all the temperature range thanks to an adaptation of the energy management parameter.

1. Introduction

The electrical network embedded in an aircraft is composed of several electrical sources and some of them are storage components [1]. Aircrafts make use of Energy Storage Systems (ESS) to provide all or some of the energetic requirements, according to the hybridization rate and to the mission profile. In some cases, the Electrical Energy Storage Systems (EESS) provide the whole required energy when the other sources are unavailable. Indeed, they are helpful as support to engine start at the mission beginning or as electrical emergency back-up. Moreover, the reliability, stability and quality issues of embedded network can be solved by the connection of EESS to the network. In this case, they are used to fulfill the power peaks and smooth the power supplied by the main sources.

Batteries, supercapacitors, flywheels and so on [2] can be electrical storage equipment for hybrid vehicles [3,4] or for miscellaneous hybrid applications [5,6]. In the considered aircraft application, the embedded EESS are supercapacitors and secondary batteries. Secondary battery means the electrochemical cell is rechargeable, contrary to primary battery which is not rechargeable. The complementarity of these sources is demonstrated in a first part. Then, a method is presented to size EESS by taking into account their hybridization and the energy management which is developed for this application. In literature [7–9], sizing tools for supercapacitor or secondary battery systems are suggested, where

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only one source is sized at a time from its energetic requirements, and where only one cell is pre-chosen for the sizing. The tool described in this paper leads to size both EESS in parallel by choosing the suitable cell among a library. The third part deals with the study of the influence of few parameters, such as Depth-of-Discharge (DoD) and cut-off frequency, on sizing results. Finally, a validation of the sizing is suggested and the sizing validity is discussed according to the temperature.

2. The Electrical Energy Storage Systems

In our application (aircraft), two EESS are embedded: supercapacitor and Lithium-ion polymer battery systems. They were chosen because of their specific energy and power and also their technical complementary [10,11], as shown below.

In literature [3,12], Electrical Energy Storage Systems are compared through their energetic characteristics (energy and power) via Ragone plots [13]. It is also interesting to list other characteristics, which have a great impact on the use of such devices. A suggestion to compare easily different EESS is to group some characteristics together in a spider web diagram. This plot needs beforehand to define a scale for each characteristic. A five-level scale, where the fifth level indicates the best performance, is suggested in Table 1. The comparison is carried out on six criteria, which are specific energy and power, discharge time, life duration, energetic efficiency and auto-discharge rate. Other criteria, such as reliability, recyclability, technology maturity and so on, could be added. But they are not considered in this study because they are qualitative criteria (technology maturity) or they depend strongly on the use conditions (reliability for instance), and this kind of plot needs quantitative information.

For supercapacitor or Double-Layer Capacitor (DLC) systems, the specific energy is between 5 and 15 Wh kg^{-1} and the specific power is between 800 and 2000 W kg^{-1}, according to [3]. The time constant for supercapacitor discharge is rather low in comparison with time constants of other storage systems. The discharge time is about few seconds [3]. In these components, the electrical power is directly stored as electrostatic power without any energy conversion. Therefore, the stored electrical power can be quickly supplied and the number of cycles is high: between 100,000 and 500,000 [14]. An advantage is their energetic efficiency which is between 95 and 98% [3], [12] and a drawback is the quite important auto-discharge rate, which is about 5% a day [12].

As for Lithium-ion polymer secondary battery systems [15], the specific energy is between 120 and 140 Wh kg^{-1} and the specific power is between 10 and 1000 W kg^{-1}. Their discharge time is about several minutes or hours. Actually, it depends on the discharge current-rate. The life duration of Lithium battery is higher than life duration of other battery technologies (Nickel or Lead). The number of cycles is around 1500 for Lithium-ion polymer batteries. This kind of battery has also two advantages: an excellent energetic efficiency (close to 100% because of the non-aqueous electrolyte) and a low auto-discharge rate, which is between 0.1 and 0.5% a day.

Table 1
Evaluation scale for criteria to compare Electrical Energy Storage System characteristics.

Level	1	2	3	4	5
Specific energy [Wh kg^{-1}]	<5	5 − 30	30 − 100	100 − 200	>200
Specific power [W kg^{-1}]	10 − 10^2	10 − 10^3	10^2 − 10^3	10^2 − 10^4	>10^4
Discharge time [s]	<0.01	0.01 − −1	1 − 100	100 − 10^3	>10^3
Number of cycles	<10^3	10^3 − 2.10^3	2.10^3 − 10^5	10^5 − 10^6	>10^6
Efficiency [%]	<50	50 − 75	75 − 90	90 − 98	>98
Auto-discharge [% a day]	>5	1 − 5	0.5 − 1	0.1 − 0.5	<0.1

The comparison between supercapacitor and Lithium-ion polymer battery systems is given on the spider web diagram on Fig. 1. These components are complementary in terms of energetic performances. Indeed, supercapacitors are usually considered as a power source, able to provide or recover power peaks; whereas secondary batteries are considered as an energy source, capable of providing power during a long time. Moreover, they are complementary on other characteristics, which are as interesting as energetic performances: discharge time, life duration (number of cycles) and auto-discharge.

3. Sizing of Electrical Energy Storage Systems

Sizing of Electrical Energy Storage Systems consists in determining the appropriate cell and the necessary number of cells for each system in order to meet the energetic requirements of the application, while considering the environment constraints and their own technological limits.

First, the input data of the EESS sizing tool are the required performances, that is to say the energetic characteristics, such as energy and power, which EESS can provide or recover. The energetic requirements of the application are usually represented in the form of load profiles [16], [17] or driving cycles [4–6]. Therefore, the load profile defined for our application (aircraft) is given and the way to share out this profile between both storage components is explained.

Then, the constraints applied on the whole system by its environment are reviewed. Indeed, various constraints have to be taken into account to size EESS.

After the definition of the input data and the environmental constraints, the sizing tool is described through algorithms, and the optimization criterion is specified. In aircraft, the criterion to be minimized is the weight as critical for this application. It could be of course other criteria in other applications, such as cost [17], volume, internal resistance to reduce the losses due to Joule effect, and so on.

Finally, the sizing results are given. The output data of the sizing tool are the appropriate cell and the number of cells for each EESS, their energetic performances and the global weight of the storage systems.

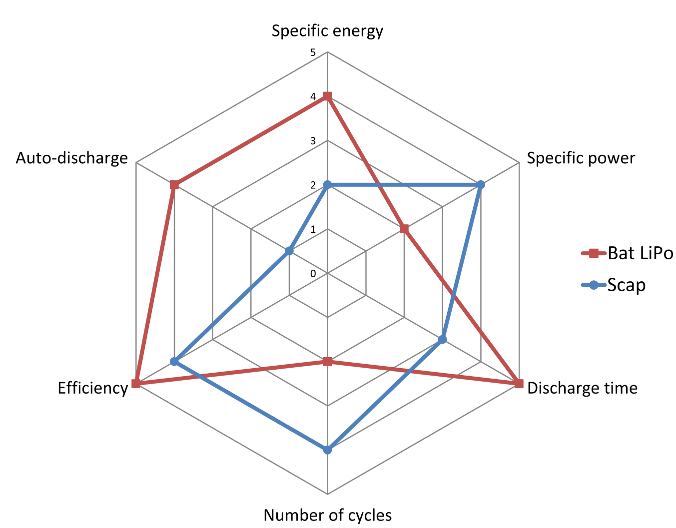


Fig. 1. Spider web diagram for comparison of supercapacitor and Li-ion polymer battery characteristics.

3.1. Input data: required energetic performances

The input data of the sizing tool are the energetic requirements, in other words the load profile. On next paragraphs, the load profile is defined and the influence of the electrical architecture and the impact of the strategy of energy management on the way to share out the required energy between the sources are explained.

3.1.1. Load profile

The sizing of EESS is carried out with a load profile, extracted from mission profile. Actually, a mission profile is composed of a succession of operating modes (ground control, turbine start, take-off phase, in flight operations, landing phase, and so on), which can vary according to the mission type. Among all the possible mission profiles, a typical one is chosen and is used for the load profile determination. Thus, a load profile is a succession of load consumption profiles which can be either constant profiles (background loads) or variable profiles (specific loads). This typical load profile defines the energetic requirements for the complete electrical network which have to be supplied by the electrical sources.

3.1.2. Electrical architecture

The studied aircraft electrical architecture is composed of devices to generate electrical energy, to distribute it, to convert it and to store it on board. There are a generator, which provides the average power, and EESS to compensate or to replace the generator when it is necessary (in case of failure for instance or when it is not yet started). The way to connect these sources to the network has an influence on their use. In the next paragraph, different solutions to associate two storage systems and to connect them to the network are reviewed.

As a matter of fact, there are different solutions to associate two Electrical Energy Storage Systems and to connect them to a network [2]: a direct electrical coupling (also called passive hybridization) or coupling via converters.

The first association is a passive hybridization, that is to say a direct electrical coupling between several EESS. In this case (Fig. 2a), the voltage is the same at the terminals of all the devices. Most of the time, voltage variations are restricted for network quality and stability reasons. Therefore, the voltage operating range of EESS is scaled-down, and it is difficult to make the best use of these storage devices and no degree of freedom is available for the dispatching of the power. The advantages of this kind of association are its simplicity, its low cost, the gain of weight and a better efficiency (no loss in converter) [5]. This passive hybrid association is used when system control is not mandatory. Usually, when an energy or power management is not possible, the choice of EESS is done so that their electrical characteristics are complementary. Indeed, the sharing out of energy requirements between EESS is made possible through their different impedance.

The second association is an active hybridization, where at least one component is connected to the network with a converter. A converter is used for the voltage adaptation and the galvanic isolation (or device decoupling). An electrical architecture with converters is suitable for energy management. In the case where one EESS is directly connected to the network (Fig. 2b), this source is considered as an energy buffer, with the same voltage as the network voltage. The other sources with their associated converters are controlled and used only when it is necessary. In the case where all the EESS are connected to the network through converters (Fig. 2c), each source is controlled so as to be used at its nominal operating point and so as to avoid operating in unfavorable conditions such as inconvenient cycling for batteries.

In an aircraft application, the network voltage variations have to be limited according to standards [18] and the power contribution of the generator should be reduced, too. To achieve these objectives, the global system needs to be controlled. Therefore an active hybridization is chosen so that the system variables (such as voltage, current, power or State-of-Charge) are controlled for all the sources. The electrical architecture studied in this paper is given on Fig. 3.

3.1.3. Energy management

Generator and Electrical Energy Storage Systems are connected to the network through converters. Different energy management strategies are developed in literature: by taking into account the topology or the source dynamic response [16]; by defining an energy hub, as an interface among energy producers, consumers and the transportation infrastructure [17]; by introducing a wavelet-fuzzy logic strategy to split the power between different sources [7]; and so on.

In the considered application, an energy management strategy is implemented so that the electrical requirements are assigned to the three sources [19], as follow: supercapacitors, which are considered as a power source, provide pulse power; secondary battery, which is considered as an energy source, provides transient power with a slower dynamic response than supercapacitor's one; the generator provides the average power with slow dynamics. This energy management is based on a frequency approach, as developed in [20]. Two low-pass filters (characterized by two cut-off frequencies f_{C0} and f_{C1}) are used to obtain the power mission for each source (Fig. 4). High frequency power is assigned to the supercapacitor system (SCAP), low frequency power to the generator (GEN) and intermediate frequency power is assigned to the battery (BAT). For the sizing of storage devices, the low frequency power provided by the generator is not studied. Thus, the cut-off frequency of the first low-pass filter f_{C0} is fixed so as to avoid quick power variations for generator. The cut-off frequency of the second low-pass filter f_{C1} is variable and used as setting parameter to minimize the weight of storage components.

3.2. Constraints on the EESS sizing

A first kind of constraints is the technological limits of the system, such as the maximal current acceptable by cells, or the minimum and maximum cell voltages.

A second kind of constraints is the environment influence on the system. As devices are operated in a global system, interactions between the environment and them must be studied. For example,

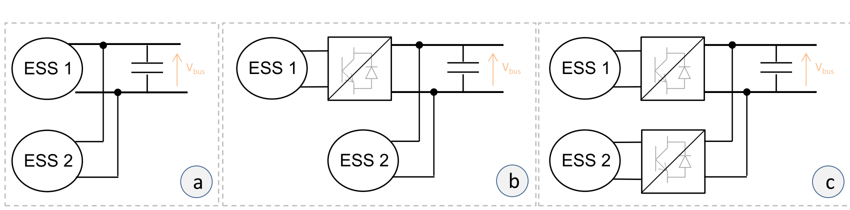


Fig. 2. How to associate two Energy Storage Systems and to connect them to an electrical network.

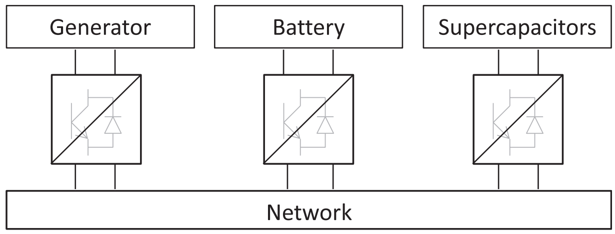


Fig. 3. Example of electrical architecture for an aircraft.

Table 2
Constraints on EESS sizing.

I_{max_bat}	[A]	Maximum current for a battery cell
I_{max_scap}	[A]	Maximum current for a supercapacitor
U_{max_bat}	[V]	Maximum voltage for a battery cell
U_{max_scap}	[V]	Maximum voltage for a supercapacitor
U_{min_bat}	[V]	Minimum voltage for a battery cell
U_{min_scap}	[V]	Minimum voltage for a supercapacitor
U_{bus}	[V]	Network voltage
DOD		Depth-of-discharge for a battery cell
D		Depth-of-discharge for a supercapacitor

the device voltage is linked to the network voltage. Considering the electrical architecture, the storage systems are connected to the network through converters. Thus, the EESS voltage can be different from the network voltage.

Finally, another constraint is the authorized Depth-of-Discharge (DoD) for storage systems. The DoD is the useful energy related to maximum stored energy. In some configurations, it is recommended keeping the State-of-Charge (SoC) in a given range to face possible failure or disoperation. These various constraints are summed up in Table 2.

3.3. Method for supercapacitor bank and secondary battery sizing

Before describing the complete sizing tool, both algorithms for sizing a supercapacitor system and a battery system are presented.

The sizing of a supercapacitor system is carried out by considering a supercapacitor cell, which characteristics based on a standard model [21,22] (Fig. 5) are summed up in Table 3.

The sizing of a battery system is carried out by considering a battery cell, which characteristics based on a quasi-static model, also called Thévenin equivalent model [23] (Fig. 6), are summed up in Table 4.

The sizing method for both storage systems is presented by means of an algorithm (Fig. 7) and mathematically detailed below, step by step.

The input data come from the low-pass filter, which shares out the load profile between both storage systems. For supercapacitor system, the input data are useful energy $W_{u\_SCAP\_req}$ and maximal power P_{max_req}. For secondary battery system, they are useful energy $W_{u\_BAT\_req}$, maximal power P_{max_req}.

Step 1: Determination of the maximal energy from the useful energy, by taking into account the Depth-of-Discharge ratio for each source (d_{req} for supercapacitor and DOD_{req} for battery):

$$W_{max\_SCAP\_req} = W_{u\_SCAP\_req} \Big/ \left(1 - d_{req}^2\right) \tag{1}$$

$$W_{max\_BAT\_req} = W_{u\_BAT\_req} / DOD_{req} \tag{2}$$

With: $W_{max\_SCAP\_req}$ the maximal energy for supercapacitor bank

and $W_{max\_BAT\_req}$ the maximal energy for secondary battery

Step 2: Determination of cell number necessary to provide the required maximal energy.

$$N_{scap\_req} = W_{max\_SCAP\_req} / W_{max\_scap} \tag{3}$$

$$N_{bat\_req} = W_{max\_BAT\_req} / W_{max\_bat} \tag{4}$$

With: N_{scap_req} the necessary cell number for supercapacitor bank

and N_{bat_req} the necessary cell number for secondary battery

Step 3: Determination of the maximal required current for a cell.

$$I_{max\_scap\_req} = U_{scap}/(2R_{scap}) - \left(\left(N_{scap\_req} \cdot U_{scap}\right)^2 - 4N_{scap\_req} \cdot R_{scap} \cdot P_{max\_req}\right)^{1/2} / \left(2N_{scap\_req} \cdot R_{scap}\right) \tag{5}$$

$$I_{max\_bat\_req} = E_{0\_bat}/(2R_{bat}) - \left(\left(N_{bat\_req} \cdot E_{0\_bat}\right)^2 - 4N_{bat\_req} \cdot R_{bat} \cdot P_{max\_req}\right)^{1/2} \Big/ \left(2N_{bat\_req} \cdot R_{bat}\right) \tag{6}$$

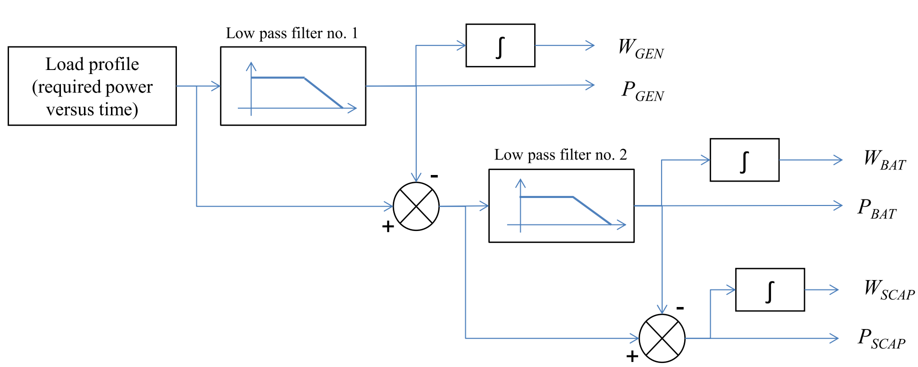


Fig. 4. Energy management based on a frequency approach adapted to three sources.

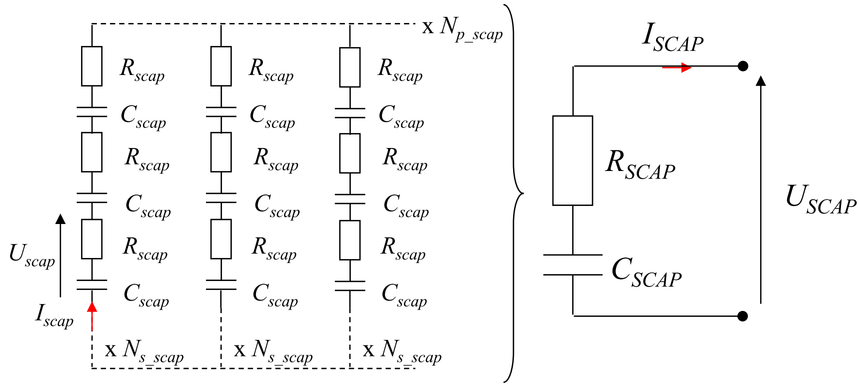


Fig. 5. Electrical equivalent circuit of a supercapacitor system (standard model).

With: $I_{max\_scap\_req}$ the maximal required current for a supercapacitor cell

and $I_{max\_bat\_req}$ the maximal required current for a battery cell

Step 4: Comparison between the maximal required current and the maximal current acceptable by a cell.

In the case where the maximal required current is lower than the maximal current acceptable by a cell, the cell numbers in serial and in parallel are determined from the network voltage requirement. As choppers associated to the storage systems are boost-converters, the maximal voltage of each storage system must be lower than the minimal network voltage U_{min_bus}, as described in Eq. (7) and in Eq. (8).

$$U_{SCAP} \le U_{min\_bus} \quad (7)$$

$$U_{BAT} \le U_{min\_bus} \quad (8)$$

The cell numbers in serial, N_{s_scap} and N_{s_bat}, are determined to respect this requirement.

$$N_{s\_scap} \le U_{min\_bus}/U_{max\_scap} \quad (9)$$

$$N_{s\_bat} \le U_{min\_bus}/U_{max\_bat} \quad (10)$$

The cell numbers in parallel, N_{p_scap} and N_{p_bat}, are deduced from the cell numbers in serial and the required cell numbers.

$$N_{p\_scap} \ge N_{scap\_req}/N_{s\_scap} \quad (11)$$

$$N_{p\_bat} \ge N_{bat\_req}\big/N_{s\_bat} \quad (12)$$

In the case where the maximal required current is higher than the maximal current acceptable by a cell, the cell number in serial is determined from the network voltage requirement, expressed in Eqs. (7) and (8). The cell number in parallel is determined with Eqs.

Table 3
Characteristics of a supercapacitor cell.

R_{scap}	[Ω]	Internal resistance
C_{scap}	[F]	Capacitance
U_{max_scap}	[V]	Maximum voltage
I_{max_scap}	[A]	Maximum current
m_{scap}	[g]	Cell weight
v_{scap}	[l]	Cell volume
d		Depth-of-Discharge ratio
W_{max_scap}	[J]	Maximum energy ($= ½C_{scap}.U_{max\_scap}{}^2$)

Table 4
Characteristics of a battery cell.

R_{bat}	[Ω]	Internal resistance
C_{bat}	[Ah]	Cell capacity
E_{0_bat}	[V]	Open-circuit voltage
I_{max_bat}	[A]	Maximum current
m_{bat}	[g]	Cell weight
v_{bat}	[l]	Cell volume
DOD		Depth-of-Discharge ratio
W_{max_bat}	[J]	Maximum energy ($= C_{bat}.E_{0\_bat}$)

W_{max_bat} is given for SOC = 100%.

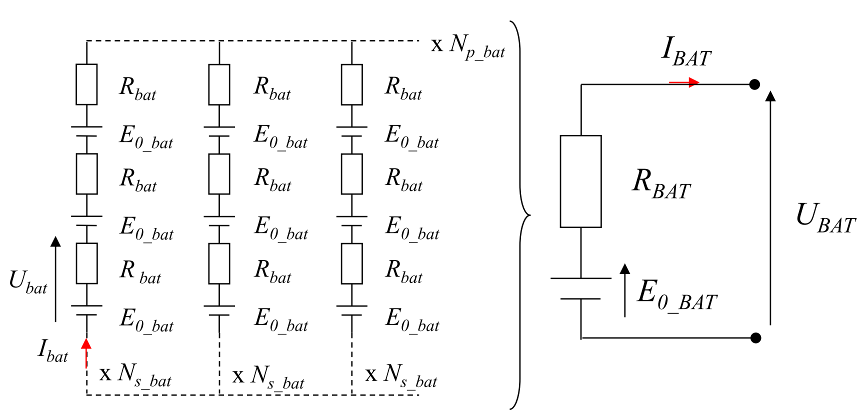


Fig. 6. Electrical equivalent circuit of a battery system (quasi-static model).

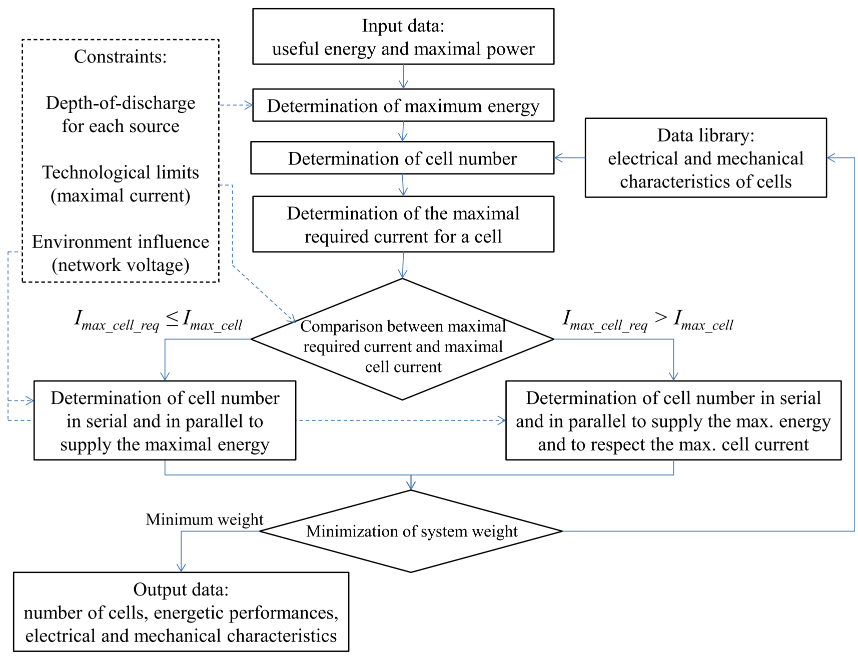


Fig. 7. Algorithm for sizing supercapacitor or battery systems.

(15) and (18) so as to conciliate the energetic requirement given in Eqs. (13) and (16), and the current limit expressed in Eqs. (14) and (17).

$$N_{p1\_scap} \geq N_{scap\_req}/N_{s\_scap} \tag{13}$$

$$N_{p2\_scap} \geq I_{max\_scap\_req}/I_{max\_scap} \tag{14}$$

$$N_{p\_scap} = \max(N_{p1\_scap}, N_{p2\_scap}) \tag{15}$$

$$N_{p1\_bat} \geq N_{bat\_req}\Big/N_{s\_bat} \tag{16}$$

$$N_{p2\_bat} \geq I_{max\_bat\_req}/I_{max\_bat} \tag{17}$$

$$N_{p\_bat} = \max(N_{p1\_bat}, N_{p2\_bat}) \tag{18}$$

Step 5: Determination of the appropriate cell to minimize the system weight.

This sizing method is led with a finite loop to review each cell from a data library given in Table 5 for supercapacitor [14] and in Table 6 for battery [15]. Most of the time in literature [7–9], only one cell is pre-chosen and the sizing is carried out by considering only this cell.

The algorithm leads to determine the appropriate cell for which the storage system weight is minimal.

Step 6: Determination of the results.

The output data are for the supercapacitor system: cell number N_{scap} (in serial N_{s_scap} and in parallel N_{p_scap}, with $N_{scap} = N_{s\_scap} \cdot N_{p\_scap}$), energetic performances (W_{SCAP} and P_{max_SCAP}) and electrical and mechanical characteristics: storage capacity C_{SCAP}, internal resistance R_{SCAP}, and system weight m_{SCAP} and volume v_{SCAP}.

For the battery system, they are: cell number N_{bat} (in serial N_{s_bat} and in parallel N_{p_bat}, with $N_{bat} = N_{s\_bat} \cdot N_{p\_bat}$), energetic performances (W_{BAT} and P_{max_BAT}) and electrical and mechanical characteristics: storage capacity C_{BAT}, internal resistance R_{BAT}, and system weight m_{BAT} and volume v_{BAT}.

3.4. Sizing of the whole storage system

Most of the time, the sizes of supercapacitor and secondary battery systems are obtained independently of each other, from energetic requirements (input data) which are set for each source at the sizing beginning. The aims of the tool described in this paper are to size at the same time the supercapacitor and the secondary

Table 5
Supercapacitor cell database for the system sizing tool.

Supercapacitor						
C_{scap}	[F]	650	1200	1500	2000	3000
R_{scap}	[mΩ]	0.8	0.58	0.47	0.35	0.29
U_{scap}	[V]	2.7	2.7	2.7	2.7	2.7
U_{max_scap}	[V]	2.8	2.8	2.8	2.8	2.8
I_{max_scap}	[A]	105	110	115	125	150
m_{scap}	[g]	200	300	320	400	550
v_{scap}	[dm^3]	0.15	0.233	0.264	0.312	0.411
P_{max_scap}	[kW kg^{-1}]	11.4	10.5	12.1	13.0	11.4
W_{max_scap}	[Wh kg^{-1}]	3.29	4.05	4.75	5.06	5.52

Datasheets from Maxwell.

Table 6
Battery cell database for the system sizing tool.

Battery						
C_{scap}	[Ah]	0.8	2	4.8	8	16
R_{scap}	[mΩ]	12	8	11	4.5	2
E_0	[V]	3.7	3.7	3.7	3.7	3.7
U_{max_bat}	[V]	4.2	4.2	4.2	4.2	4.2
I_{max_bat}	[A]	24	30	96	16	32
m_{bat}	[g]	23	50	115	160	307
v_{bat}	[dm^3]	0.013	0.029	0.065	0.080	0.167
P_{max_bat}	[W kg^{-1}]	3860	2220	3090	370	386
W_{max_bat}	[Wh kg^{-1}]	129	148	154	185	193

Datasheets from Kokam.

battery systems and to minimize their total weight by acting on the cell choice among a library and on the dispatching of the energetic requirements between both of ESS.

The tool for sizing the whole storage system is implemented in Matlab® and is described with the algorithm in Fig. 8. The load profile is shared out, by the means of a low-pass filter, between both storage systems. Therefore, the energy requirements for each EESS, depending on the cut-off frequency of the low-pass filter, are the input data for each sizing algorithm. Both algorithms are solved in parallel so as to define the cell number and the suitable cell which lead to the minimum ESS weight. Then, an outer loop acts on the low-pass filter frequency f_{C1} to change the way to share out the energetic requirements. In this way, the influence of the cut-off frequency on the sizing is studied and the appropriate cut-off frequency is determined to minimize the weight of the whole storage system.

3.5. Output data

The output data are the results of the sizing: the most appropriate cell for each Electrical Energy Storage System, the cell numbers (and their serial or parallel association), the energetic performances of each EESS and their electrical and mechanical characteristics (storage capacity, internal resistance, weight, volume, and so on).

4. Analysis of sizing results

Results of sizing are presented in order to underline the influence of Depth-of-Discharge on the storage system weight. On the other hand, the influence of the cut-off frequency on the energetic assignment for each EESS and on the global weight is studied.

4.1. Influence of depth-of-discharge on sizing

As shown in Eqs. (19) and (20), the Depth-of-Discharge (DoD) is in relation with the authorized voltage of the sources. Therefore, it

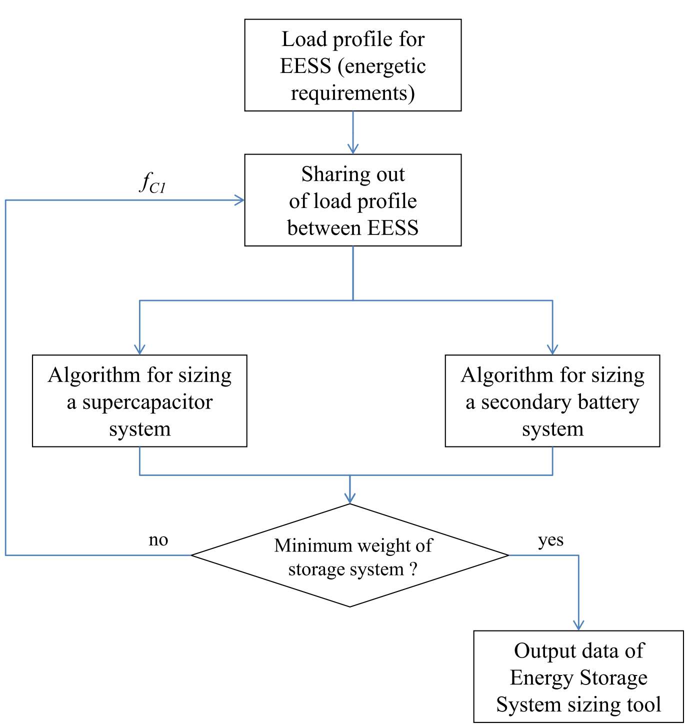


Fig. 8. Algorithm for Electrical Energy Storage System sizing.

is also in relation with the architecture of the electrical network. As converters are integrated into the electrical architecture, the storage system voltage is quite independent on the network voltage.

$$\text{From (1)}, \quad \left(1-d^2\right) = W_{u\_SCAP}/W_{max\_SCAP} \quad \text{and} \quad d = U_{scap}/U_{max\_scap} \tag{19}$$

$$\text{From (2)}, \quad \text{DOD} = W_{u\_BAT}/W_{max\_BAT} \quad \text{and} \quad \text{DOD} = E_0/E_{0\_max} \tag{20}$$

With: E_{0_max} the open-circuit voltage corresponding to SOC = 100%

In Fig. 9, the relative weight of both storage systems is given for different values of DoD. The higher the authorized Depth-of-Discharge is, the lower the storage system weight is. For the remaining studies, the Depth-of-Discharge is set at 75% for having an available energy reserve in case of emergency, for example in order to supply the power necessary to land the aircraft in case of major failure of the main generator. Actually, a DoD of 75% corresponds to a voltage variation of 50% for a supercapacitor system and one of 37% for the Lithium-ion polymer battery system.

4.2. Influence of cut-off frequency on sizing

The sizing algorithm computes the cut-off frequency which minimizes the weight of the whole storage system. For that purpose, a frequency range, from 0.5 mHz to 20 mHz, is reviewed. The evolution of the power and the energy required for both storage systems is given in Fig. 10 and Fig. 11, for different values of the cut-off frequency. On Fig. 10, it can be observed that the required power for supercapacitor system is bigger than the required power for battery system, in agreement with the energy management described before. Fig. 11 shows that the global energy remains constant and only the energetic assignment of both sources changes according to the cut-off frequency. On Fig. 12, the evolution of the storage system weight is presented for different cut-off frequency values. The weight is minimal for a cut-off frequency between 4 and 10 mHz. The weight of supercapacitor system is dominating in comparison with the weight of battery system. At frequencies lower than 5 mHz, the supercapacitor system is sized in regards to required energy, which is substantial. The higher the cut-off frequency is, the lower the energy required for this system is. At frequencies higher than 10 mHz, the required power for supercapacitor system is still high and its sizing is carried out essentially in regards to power.

5. Validation of sizing by simulation

In this paragraph, a validation of the sizing results is suggested with a simulation of the storage system behavior in response to the typical load profile. Then the sizing validity is discussed according to the temperature. It is interesting to assess its influence on the sized EESS behavior because this environmental constraint is not taken into account in the sizing algorithm and it can have a substantial impact on storage component performances.

5.1. Validation of sizing at ambient temperature

To validate the sizing results, a simulation is carried out with behavioral models of the chosen ESS cells. From the sizing algorithm, the minimum weight is obtained with a certain combination of supercapacitor cells and Lithium-ion battery cells. Therefore, these cells were tested and the parameters of their models were defined from these characterization tests. The cell models are

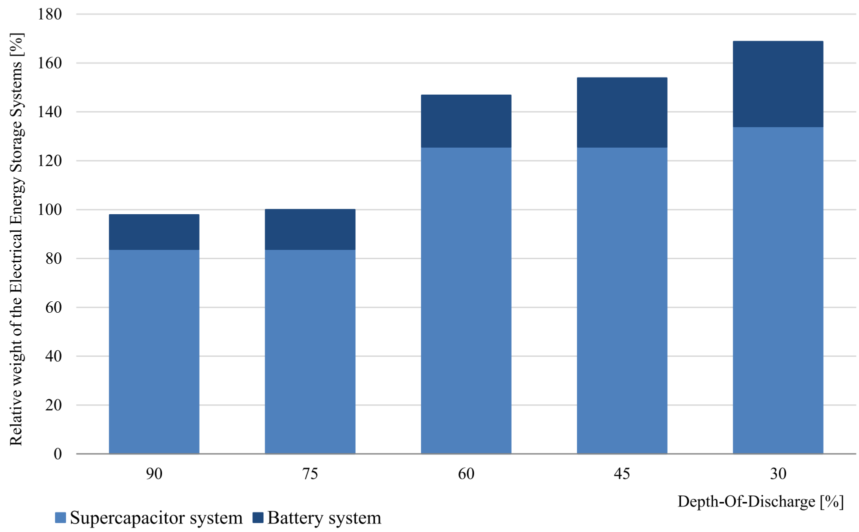


Fig. 9. Relative weight of both storage systems for different Depths-of-Discharge.

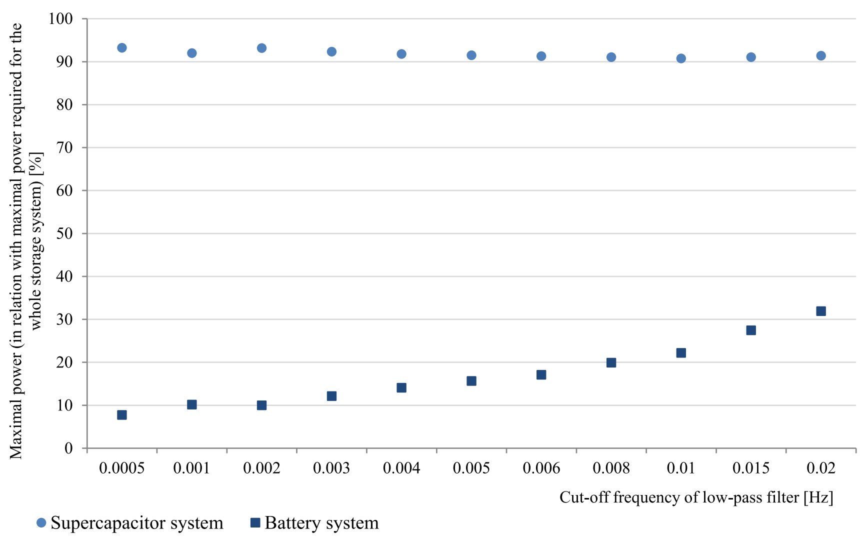


Fig. 10. Cut-off frequency influence on required power for both storage systems.

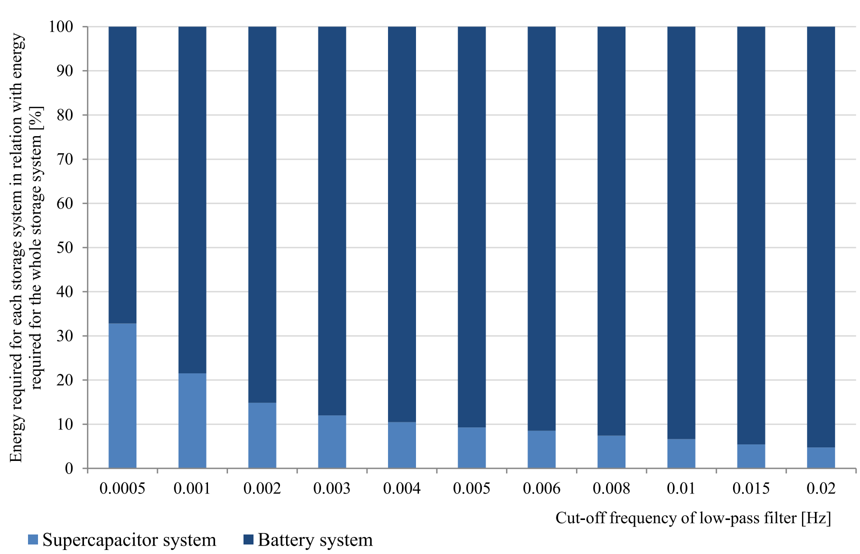


Fig. 11. Cut-off frequency influence on required energy for both storage systems.

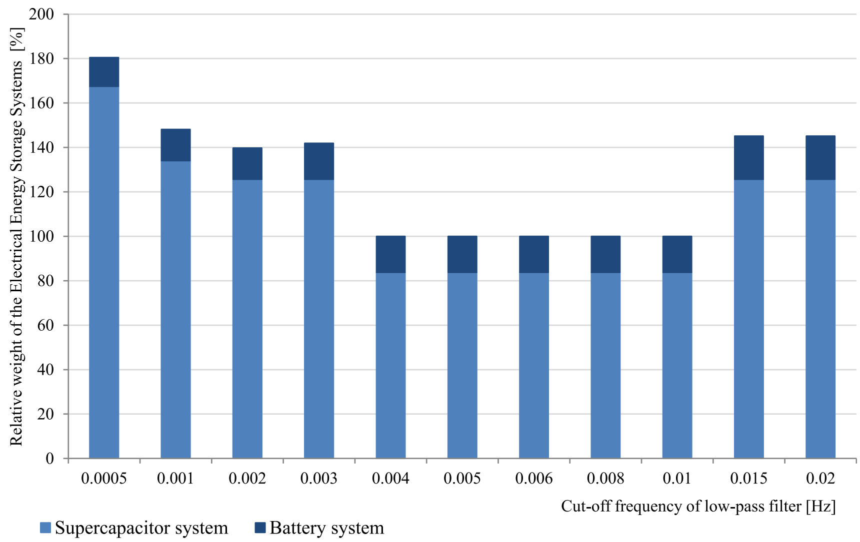


Fig. 12. Cut-off frequency influence on weight of the whole storage system.

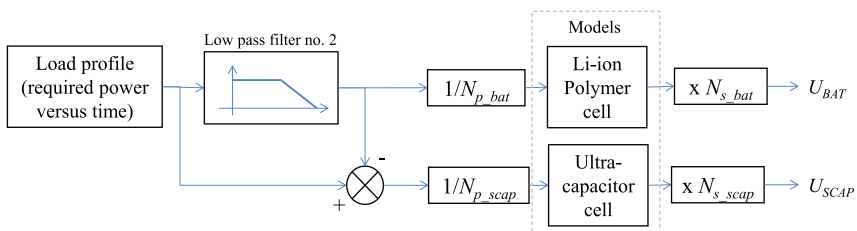
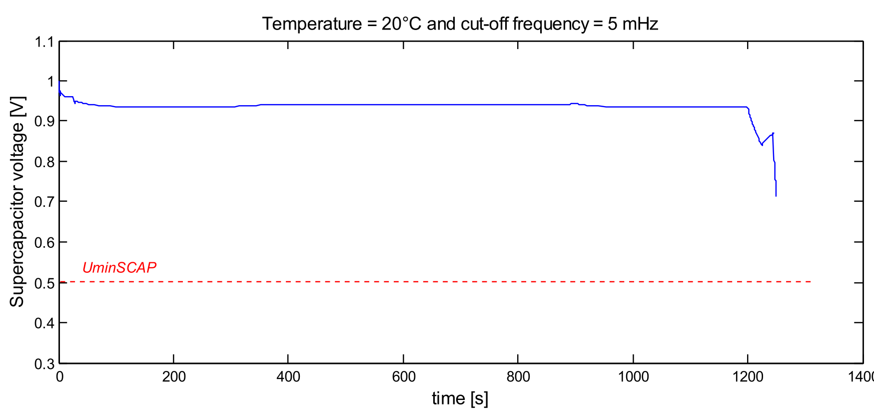


Fig. 13. Validation of Electrical Energy Storage System sizing by simulation.



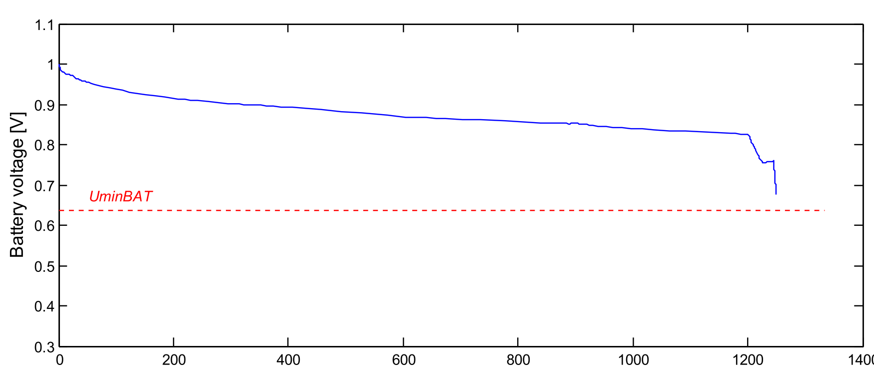


Fig. 14. Simulation of storage system operation with a load profile at 20 °C – Evolution of EESS voltages.

implemented in Matlab® Simulink for the simulation, as shown on Fig. 13. To check the sizing, the considered load profile is shared out between both storage systems, as designed by the sizing algorithm, according to the frequency approach explained before. The cut-off frequency used for simulation is the frequency (5 mHz) which led to the minimal weight for the whole storage system. To sum up, the sizing results are assessed by simulation with behavioral models, in the same conditions as those used for the sizing: the same load profile, the suitable cut-off frequency and at ambient temperature (20 °C).

Actually, a first simulation is carried out in the conditions described before. In Fig. 14, the evolution of the storage system voltages is plotted and their minimal values are given, too. The supercapacitor system provides a power at high frequencies and the battery system provides the energy. At the end of the load profile, their voltages tend to their minimal values. The sizing results are in good agreement with the energetic requirements. The devices are well-sized according to the load profile.

5.2. Evaluation of sizing at lower temperature

The second step of the validation is to check if the sizing is still valid on the whole operating range. In particular, it is interesting to study the influence of temperature. Currently, the sizing validity is checked only at one temperature, and most of the time at ambient temperature (or temperature considered in the sizing tool). In our case, the developed models take into account the component behavior in regards to temperature, as characterization tests were carried out at different temperatures. For example, the model of the 650F-cell includes the temperature impact on its inner resistance [22]. This previous work is useful to evaluate the sizing results at different temperatures.

Thus, another simulation is carried out at a lower temperature (0 °C) because this temperature can be critical for storage systems. In Fig. 15, the voltages of supercapacitor system and battery system are plotted. At that temperature, the battery voltage falls down under its minimal value at the end of the profile. As a matter of fact, the battery system, which is well-sized at 20 °C, is undersized for an operation at 0 °C. Indeed, the battery performances are dramatically reduced at low temperature, whereas temperature has no impact on supercapacitor system.

5.3. Evolution at low temperature

In the previous paragraph, the tremendous impact of low temperature on battery behavior was observed and that is a problem for the sizing validity. The adaptation of the sizing tool in order to integrate the temperature influence on parameters could be a solution, but there are few drawbacks. The first drawback is the data library which must be completed either with supplier's data (if they are available at different temperatures), or with reliable experimental data (which needs a lot of characterization tests). Another drawback is the new sizing result. In fact, it should be valid in the worst case of temperature, but could be oversized for the remaining operating range. In an aircraft application, oversizing means overweight and that is not acceptable.

A solution is suggested in this paper to avoid a new sizing at another temperature than 20 °C. This solution consists in keeping

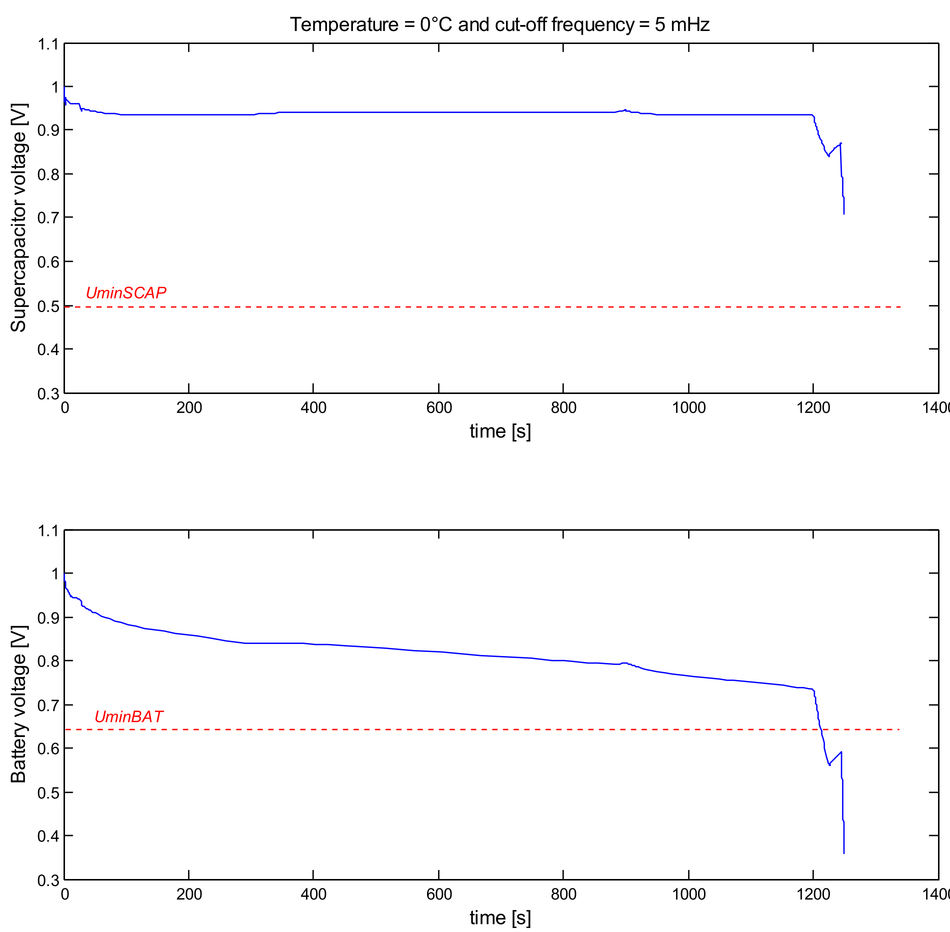


Fig. 15. Simulation of storage system operation with a load profile at 0 °C – Evolution of EESS voltages.

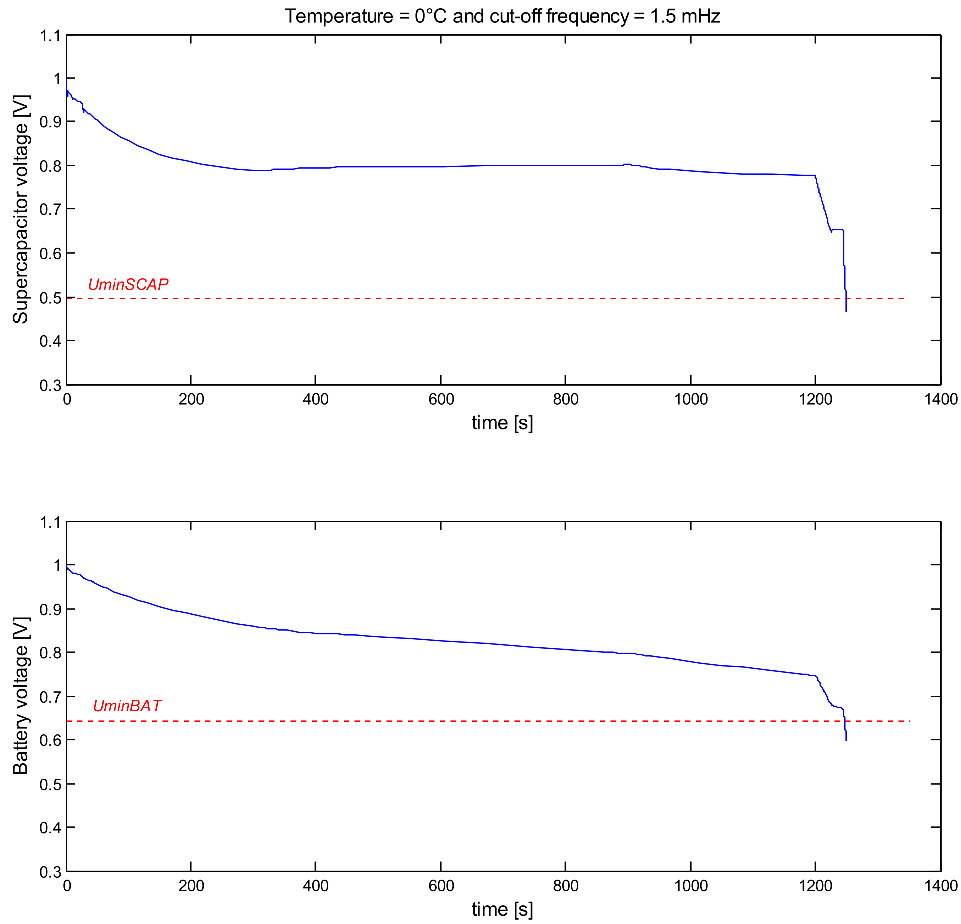


Fig. 16. Simulation of storage system operation with a load profile at 0 °C – Evolution of EESS voltages with an adapted cut-off frequency.

the sizing results obtained with supplier's data at 20 °C and in acting on the cut-off frequency of the low-pass filter to change the energetic assignment for both storage systems. As a matter of fact, battery is more sensitive to temperature effect than supercapacitor. Thus, at low temperature, the energetic requirements for supercapacitor system can be increased, and this is possible by modifying the cut-off frequency.

Simulation results are given in Fig. 16 with a cut-off frequency of 1.5 mHz. In this case, the Depth-of-Discharge is about 75% for supercapacitor and battery systems.

In this case, supercapacitor system is used as a power source but as an energy source as well: its State-of-Charge is about 25% at the end of the profile. As a consequence, the battery Depth-of-Discharge becomes suitable again at the end of the profile.

Eventually, the sizing results obtained at 20 °C is still valid at 0 °C by means of an adaptation of the cut-off frequency in the energy management strategy. The complementarity of EESS (supercapacitor and battery systems) in terms of energetic performances and temperature behavior is helpful to reduce the storage system weight while providing the energy required by the application.

6. Conclusion

The electrical network embedded in an aircraft is composed of several electrical sources and storage systems. The sizing of Electrical Energy Storage Systems is a milestone for their development and implementation in Hybrid and Electric Vehicles. In this paper, the sizing of EESS (supercapacitor and secondary battery systems) is carried out by taking into account the environment of the storage devices (connection to the network with or without converter) and an energy management based on a frequency approach. A sizing tool is presented with an optimization criterion in relation with the aircraft application: global storage system weight. Through this tool, supercapacitor and battery systems are sized in parallel. In fact, the energetic requirements for each device are linked because the load profile is shared out with a low-pass filter (high frequency power for supercapacitor system and intermediate frequency power for battery system). The influence of the cut-off frequency of the low-pass filter is studied and the frequency, which leads to the minimal weight, is determined. Finally a validation of the sizing results is carried out through simulations of cell models at different temperatures. As it is difficult for sizing results to be still valid on the whole operating range (particularly at low temperature), a solution is developed to adapt the dispatching of energetic requirements between both storage systems according to temperature, while keeping the initial sizing. This solution consists in acting on the cut-off frequency to limit the energy supplied by the battery (which performances are reduced at low temperature) and to request more energy from the supercapacitor system. By this way, the sizing determined with the algorithm is valid on the temperature range thanks to an adaptation of the energy management between the sources.

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